

## **UNIT FOUR**

### **CHAPTER 8**

# **MATERIAL ANALYSIS TECHNIQUES**

## **X-RAY DIFFRACTION**

### **Introduction**

X-rays are electromagnetic waves and they should exhibit the phenomenon of diffraction. However unlike visible, X-rays cannot be diffracted by devices such as ruled diffraction gratings because of their shorter wavelengths (0.1 nm order). In 1921 German physicist Max Von Laue suggested that a crystal which consisted of a 3D array of regularly spaced atoms could serve the purpose of grating. This is possible because all the atoms in a single crystal are regularly arranged with interatomic spacing of the order of a few angstroms and this is compatible with the conditions required to be satisfied for diffraction to take place.

On the suggestion of Laue, his associates, Friedrich and Knipping later successfully demonstrated the diffraction of X-rays from a thin crystal of zinc blende (ZnS). The diffraction pattern obtained on a photographic film consisted of a central spot and a series of dark spots arranged in a definite pattern around the central spot. Such a pattern is called the Laue's pattern and reflects the symmetry of the crystal. After that the phenomenon of X-ray diffraction has become an invaluable tool to determine the structure of crystals. It is also used to determine the wavelengths of X-rays.

### **Braggs' law**

In 1912 W.H. Bragg and W.L. Bragg put forward a model which generates the conditions for diffraction in a simple way. Accord-

∴ The interplanar distance,  $d = \frac{a}{(h^2 + k^2 + l^2)^{1/2}}$

This is denoted by  $d_{hkl}$

$$\text{Thus } d_{100} = \frac{a}{(1^2 + 0^2 + 0^2)^{1/2}} = a$$

$$d_{110} = \frac{a}{\sqrt{1^2 + 1^2 + 0^2}} = \frac{a}{\sqrt{2}}$$

$$d_{111} = \frac{a}{\sqrt{1^2 + 1^2 + 1^2}} = \frac{a}{\sqrt{3}}$$

$$\text{Thus } d_{100} : d_{110} : d_{111} = 1 : \frac{1}{\sqrt{2}} : \frac{1}{\sqrt{3}}$$

Similarly for fcc lattice

$$d_{100} = \frac{a}{2}, d_{110} = \frac{a}{2\sqrt{2}} \text{ and } d_{111} = \frac{a}{\sqrt{3}}$$

$$\text{For bcc lattice } d_{110} = \frac{a}{2}, d_{110} = \frac{a}{\sqrt{2}} \text{ and } d_{111} = \frac{a}{2\sqrt{3}}$$

### Example 1

Calculate the interplanar spacing for a (321) plane in a simple cubic lattice whose lattice constant is  $4.2 \times 10^{-10} \text{ m}$ .

### Solution

$$a = b = c = 4.2 \times 10^{-10} \text{ m}$$

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

For the plane (321),  $h = 3$ ,  $k = 2$  and  $l = 1$

$$d_{321} = \frac{a}{(3^2 + 2^2 + 1^2)^{\frac{1}{2}}} = \frac{a}{\sqrt{14}}$$

$$d_{321} = \frac{4.2 \times 10^{-10}}{\sqrt{14}} = 1.12 \times 10^{-10} \text{ m}$$

### Example 2

In a tetragonal lattice  $a = b = 0.25 \text{ nm}$  and  $c = 0.18 \text{ nm}$ . Deduce the lattice spacing between (111) planes

### Solution

$$d_{hkl} = \left( \frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2} \right)^{-\frac{1}{2}}$$

Here  $h = 1$ ,  $k = 1$ , and  $l = 1$

$$a = b = 0.25 \text{ nm} \text{ and } c = 0.18 \text{ nm}$$

$$d_{111} = \left[ \frac{1}{(0.25)^2} + \frac{1}{(0.25)^2} + \frac{1}{(0.18)^2} \right]^{-\frac{1}{2}} \text{ nm}$$

$$d_{111} = 0.126 \text{ nm}$$

### Braggs X-ray spectrometer

It is an apparatus devised by Bragg to verify his equation  $2d \sin \theta = n\lambda$  and hence to study the crystal structure. It consists of an X-ray tube (coolidge), two slits  $S_1$  and  $S_2$ , a turn table and an ionisation chamber. X-rays from the X-ray tube is allowed to pass through slits  $S_1$  and  $S_2$  so as to obtain a narrow beam which is then allowed to fall on a single crystal (D) mounted on the turn table. The crystal is rotated by means of the turn table to change the

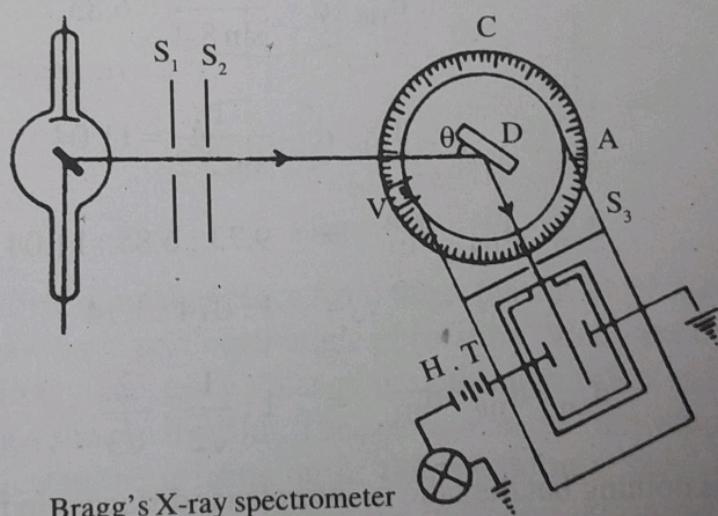
glancing angle ( $\theta$ ) at which X-rays are incident at the exposed face of the crystal. The X-rays reflected from the crystal is allowed to enter into an ionisation chamber which is used for measuring the intensities of the reflected rays. Measure the glancing angles  $\theta_1$ ,  $\theta_2$  and  $\theta_3$  corresponding to maximum intensities for  $n = 1, 2$  and  $3$ - respectively. From Bragg's equation

$$2d \sin \theta_1 = \lambda \quad \text{for } n = 1$$

$$2d \sin \theta_2 = 2\lambda \quad \text{for } n = 2$$

$$2d \sin \theta_3 = 3\lambda \quad \text{for } n = 3$$

Knowing the glancing angles and  $\lambda$  we can determine the interplanar spacings. This is repeated for different planes.



**Figure 8.3**

The structure of NaCl crystal was studied by using Bragg's spectrometer. The ionisation current was determined for different glancing angles. A graph was plotted between glancing angle and the ionisation current.

It was found from the graph that the first order reflection maxima occurred at  $5.9^\circ$ ,  $8.4^\circ$  and  $5.2^\circ$  for  $(1\ 0\ 0)$ ,  $(1\ 1\ 0)$  and  $(1\ 1\ 1)$  planes respectively.

From Bragg's equation we have

$$2d \sin \theta = n\lambda$$

$$2d \sin \theta = \lambda \text{ for } n=1$$

i.e.,  $d \propto \frac{1}{\sin \theta}$

$$d_{100} \propto \frac{1}{\sin 5.9} = 9.73$$

$$d_{110} \propto \frac{1}{\sin 8.4} = 6.85$$

$$d_{111} \propto \frac{1}{\sin 5.2} = 11.04$$

or  $d_{100} : d_{110} : d_{111} = 9.73 : 6.85 : 11.04$

$$= 1 : 074 : 1.14$$

i.e.,  $d_{100} : d_{110} : d_{111} = 1 : \frac{1}{\sqrt{2}} : \frac{2}{\sqrt{3}}$

This is nothing but the ratio of interplanar distances in fcc structure. From this Bragg concluded that sodium chloride crystal has a face centred cubic structure.

### Rotating crystal method

A single crystal is held in the path of monochromatic radiations and is rotated about an axis. i.e.,  $\lambda$  is fixed while  $\theta$  varies. Different sets of parallel atomic planes are exposed to incident radia-

tions for different values of  $\theta$  and reflection takes place from those atomic planes for which  $d$  and  $\theta$  satisfy the Bragg's law. This method is known as the rotating crystal method.

In this method a small and well-formed single crystal is mounted perpendicular to the beam. The single crystal having dimensions of the order of 1mm is positioned at the centre of a cylindrical holder concentric with the rotating spindle as shown in figure. A photographic film is attached at the inner circular surface of the cylinder.

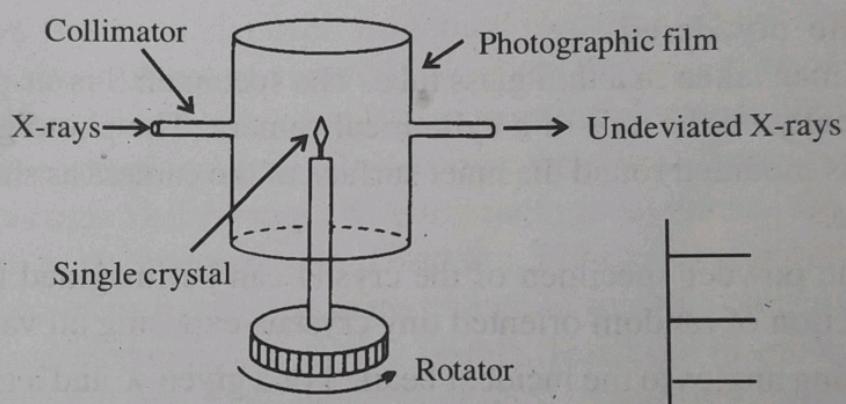


Figure 8.4

The diffraction takes place from those planes which satisfy the Bragg's law for a particular angle of rotation. When the crystal is rotated slowly successive planes pass through orientation, each producing a spot on the film. The position on the film when developed indicates the orientation of the crystal at which spot was formed. The data obtained from these spots give information about the structure of ordinary and complex molecules.

### Powder crystal method

The sample in the powdered form is placed in the path of monochromatic X-rays. i.e.,  $\lambda$  is fixed while  $\theta$  and  $d$  vary. Thus a number of small crystallites with different orientations are exposed to X-rays. The reflections take place for those values of  $d$ ,  $\theta$  and  $\lambda$

which satisfy the Bragg's law. This method is called the power method. The experimental arrangement consists of a monochromatic X-ray collimated by two slits  $S_1$  and  $S_2$  falls on the powdered specimen taken in a thin glass tube. The specimen S is suspended vertically on the axis of a cylindrical camera. The photo graphic film is mounted round the inner surface of the camera as shown in figure.

The powder specimen of the crystal can be imagined to be a collection of random oriented tiny crystals exposing all values of glancing angles to the incident beam. For a given  $\lambda$  and a given d, there can be only one value of  $\theta$  which satisfies Bragg's law. Such reflected beams emerge out from the specimen in all directions inclined at an angle  $2\theta$  with the direction of the incident beam. The reflected rays will be on the surface of a cone, vertex at the specimen, base on the photographic film and having semi vertical angle  $2\theta$ . It will be as shown in figure.

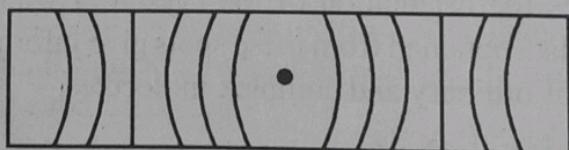


Figure 8.6

Let L be the radius of the cylindrical camera. The direct beam strikes the film at O. Suppose a spectrum with glancing angle  $\theta$  is found at A which is at a distance of R from O.

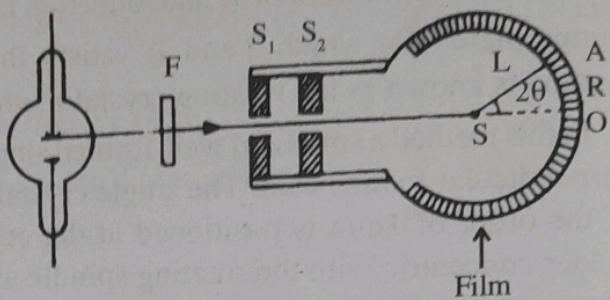


Figure 8.5: Powdered crystal method

$$\text{Then } \theta = \frac{R}{2L} \left( \text{Angle} = \frac{\text{Arc}}{\text{Radius}} \right)$$

Using this value of  $\theta$  in Bragg's equation and knowing the value of  $\lambda$ ,  $d$  the inter planar distance can be calculated. This method is employed in the study of micro crystalline substances like metals, alloys, carbon, fluroscent powders and other forms where single crystals are not available.

### Microscopic techniques

The properties of materials are decided by several factors including structural elements. Structural elements are the constituents of the structure of materials. To study the properties of materials it is necessary to examine the structural elements. Structural elements are of two types. In one type structural elements are of macroscopic dimensions. These structural elements are large enough to be observed with naked eye. For example polycrystalline specimens have large shape and grain size that constitute the structural elements, are clearly visible. However in most of the materials the structural elements grain size and shape are of microscopic dimensions. Their size is of the order of microns ( $\mu\text{m}$ ). To investigate them, we require some microscopes. The grain size and shape are termed as microstructure to investigate the microstructure of materials, commonly we use optical microscopes, electron microscopes and scanning probe microscopes. **The investigations of microstructure using microscopes is called microscopy.** Some of these techniques employ photographic equipment in conjunction with the microscope. The photograph on which the image is recorded is called photomicrograph. Many microstructural images are computer generated. Here we discuss the microscopic techniques one by one.

## Optical microscopy

Optical microscopy is an imaging techniques commonly used to study the crystal growth and kinetics of polymeric materials.

The instrument used for this is called optical microscope often referred to as the light optical microscope. It is a type of microscope that uses visible light and a system of lenses to magnify images of small samples which are opaque to visible light. The upper limit to the magnification possible with an optical microscope is approximately 2000 times.

In the case of optical microscope only the surface is subjected to observation, for this the microscope must be used in the reflecting mode. Contrasts in images produced result from differences in reflectivity of the various regions of the microstructure. Investigations of this type are often termed as metallographic, since metals were first examined using this technique.

To reveal the important details of microstructure the specimen surface must be carefully prepared. This means that first of all the surface of the specimen must be ground and to a smooth mirror like finish. This is accomplished by using successively finer abrasive papers and powders. After this surface must be coated with appropriate chemical compound to reveal the microstructure of the surface. This procedure is termed as etching. The chemical reactivity of the grains of some single phase materials depends on the crystallographic orientation. In a polycrystalline specimen etching characteristics very from grain to grain. When this specimen is viewed under a microscope we obtain the image of the surface structure. On the photographic plate used along with the microscope. The texture of each grain depends on its reflectance properties. As a consequence of etching small grooves form along chain boundaries. This is because atoms along grain boundary regions are more chemically active, they dissolve at a greater rate than

within the grains. These grooves become clearly visible when viewed under a microscope because they reflect light at an angle different from that of the grains themselves.

### Electron microscopy

Electron microscopy is a technique for obtaining high resolution images of biological and non biological specimen (metals, ceramics and polymers).

The instrument used for this is called electron microscope (EM). This instrument becomes essential when the structural elements of the specimen are too fine or small and not able to observe the images using optical microscope. We found that the maximum magnification possible in an optical microscope is only 2000 times. Whenever higher magnification than this is required we go for using electron microscope.

### Working

An image of the structure under investigation is formed using beams of electrons instead of light radiation. According to quantum mechanics the wavelength associated with an electron is

$$\lambda = \frac{h}{mv} = \frac{h}{\sqrt{2emv}} \text{ when electron is accelerated by a large voltage}$$

its wavelength  $\lambda$  is very small of the order of 3pm (0.003nm). It is due to its short wavelength the electron microscopes will have high magnification and high resolving powers (R.P), since

$$R.P \propto \frac{1}{\lambda} \text{. The electron beam is focussed and the image is formed}$$

with magnetic lenses. Both transmission and reflection beam modes of operation are possible for electron microscope.

There are two main types of electron microscope - the transmission electron microscope (TEM) and scanning electron microscope (SEM).

### **Transmission electron microscopy**

The transmission electron microscope is used to view thin specimens through which electrons can pass generating a projection image. Unlike OM, TEM brings photographs of internal microstructure of the specimen with finer details. The contrasts in the images are produced by differences in beam scattering or diffraction produced between various elements of the microstructure or defect.

The specimen material is prepared as very thin because of two reasons. Once is that solid materials are highly absorptive to electron beams the second is that thin specimen allows transmission of electron beam an appreciable fraction. The transmitted beam is projected onto a fluorescent screen or a photographic film so that image may be viewed. The magnification of TEM is about 1,000,00 times. TEM is also used in the study of dislocations.

### **Scanning electron microscopy**

In this a more powerful and useful device called scanning electron microscope (SEM) is used.

In this case the specimen material to be investigated need not be polished or etched but it must be electrically conductive. For this the surface of the specimen must be coated with a thin conductive material.

The electrically conductive surface of the specimen is scanned with an electron beam, and the reflected (or back scattered) beam of electrons is collected then displayed at the scanning race on a cathode ray tube. The image on the screen, which may be photographed represents the surface features of the specimen. The magnification of SEM is about 10 to 50,000 times are possible.

### **Scanning probe microscopy**

**Scanning probe microscopy is a branch of microscopy that**

**forms images of surfaces using a physical probe that scans the specimen.**

The scanning probe microscopes are several varieties, differs from the optical and electron microscope in that neither light nor electron is used to form an image.

SPM employs a tiny probe with a sharp tip that is brought into very close proximity (on the order of  $10^{-9}$ m) of the specimen surface. This probe is then scanned across the plane of the surface. During scanning, the probe experiences deflections perpendicular to this plane, in response to electronic or other interactions between the probe and the specimen surface. The in surface plane and out of plane motions of the probe are controlled by piezo electric ceramic components that have nanometre resolution. Furthermore these probe movements are monitored electronically and transferred to and stored in a computer, which then generates the three dimensional surface image.

Its magnification is about  $10^9$  times. Another very important thing is that SPMs may be operated in a variety of environments such as vacuum, air, liquid etc., thus a particular specimen may be examined in its most suitable environment.

### **Electron Microscope**

[Principle, construction and working]

A Microscope is a device used for obtaining a magnified image of tiny objects and its resolving power is the ability to resolve the images of two points lying close to each other.

Resolving power is measured as the reciprocal of the minimum distance (d) between two fine objects which can be seen through the microscope as separate. The distance d is given by

$$d = \frac{\lambda}{2\mu \sin \theta}$$

Where  $\lambda$  is the wave length of light used to illuminate the ob-

ject,  $\mu$  is the refractive index of the medium between the object and the objective lens and  $\theta$  is the half angle of the cone of light from the point object under observation on the objective lens. Smaller the value of  $d$ , greater will be the resolving power.

$$\text{Resolving power} = \frac{1}{d} = \frac{2\mu \sin \theta}{\lambda}. \text{ To increase the resolving}$$

power,  $\lambda$  should be made small,  $\mu$  and  $\theta$  should be made large. In the case of light (optical) microscope visible light is used to illuminate the object under observation.

It is due to diffraction of visible light the magnification and resolution are limited to 500 X or 1000 X and 0.2 micrometers respectively. In early 1930's this theoretical limit had been reached and there was a scientific desire to see the fine details of the interior structures of organic cells such as nucleus. This required 10,000 X plus magnification which was just not possible using light microscope.

After the discovery of De Broglie waves of electrons it is understood that a much shorter wave length is available which can be used to illuminate the objects under investigation so that the magnification and the resolving power can be increased drastically. Not only because of shorter wavelengths associated with fast moving electrons but also electrons are easily controlled by electric and magnetic fields. Though x-rays have shorter wave lengths it is not possible to focus them as desired.

Using the principle of De-Broglie waves first high resolution microscope was built in 1931 by the German Engineers Ernst Ruska and Maxknoll. It uses a particle beam of electrons to illuminate a specimen hence called electron microscope. The first prototype electron microscope was capable of magnifying objects by only 400 X. After several refinements electron microscopes nowadays constructed are capable of magnifying objects by 2000000 X.

Electron microscopes function exactly as their optical counterpart except that they use a focussed beam of electrons instead of visible light to image the specimen. For focusing the beam magnetic lenses are used instead of glass lenses in the case of optical microscopes.

### Uses of electron microscopes

Researchers use them to examine biological materials (such as micro organisms and cells), a variety of large molecules, medical biopsy samples, metals and crystalline samples and the characteristics of various surfaces. The electron microscope is also used extensively for inspection, quality assurance and failure analysis applications in industry.

### Scanning Tunneling microscope (STM)

The scanning tunneling microscope (STM) is a type of electron microscope that is used for viewing surfaces at the atomic level and three dimensional images of a sample.

The STM was invented by Gerd Bining and Heinrich Rohrer (at zurich) who shared the 1986 Nobel Prize with Ernst Ruska, the inventor of the electron microscope. A good STM having 0.1 nm lateral resolution and 0.01 nm depth resolution. It can be used not only on ultra high vacuum but also in air and various other liquids or gases and at temperature ranging from near zero kelvin, to a few hundred degree celsius.

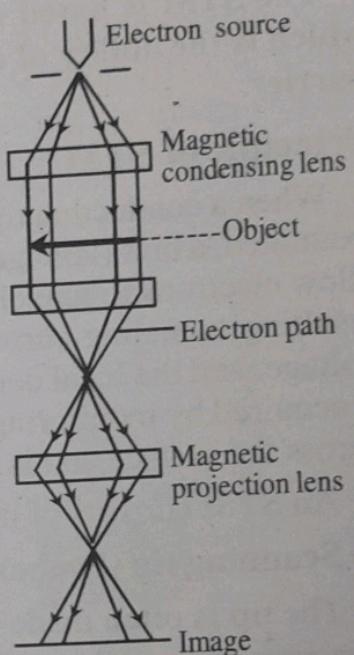


Figure : 8.7: Electron microscope schematic diagram

The STM is based on the concept of quantum tunneling, which is the ability of electrons to tunnel through a potential barrier.

### **Principle of STM**

When a conducting tip is brought very near to the surface to be examined, a bias (voltage difference) applied between the two can allow electrons to tunnel through the vacuum between them. The resulting tunneling current is a function of tip position, applied voltage, and the local density of states of the sample. Information is acquired by monitoring the current as the probe's position scans across the surface and is usually displayed in image form.

An STM consists of mainly 5 parts. They are

#### **(i) Scanning tip (Probe)**

The tip is often made of tungsten or platinum-iridium. Tungsten tips are usually made by electrochemical etching and platinum iridium tips by mechanical shearing.

#### **(ii) Piezo electric tube**

This is to control the position of the tip. The thickness of certain ceramics changes when a voltage is applied across them, a property called piezoelectricity. The changes might be several tenths of a nanometer per volt. In an STM, the piezo electric tube controls the movement of the scanning tip (probe) in x and y directions across a surface and in the z direction perpendicular to the surface.

#### **(iii) Coarse sample to tip control**

This is the mechanism through which the separation between the tip and the sample can be precisely adjusted.

#### **(iv) Vibration isolation system**

It is due to extreme sensitivity of tunnel current to height, proper vibration isolation is essential for obtaining usable results. A mechanical spring or gas spring system is often used to keep the STM free from vibrations.

### (v) Computer

Maintaining the tip position with respect to the sample, scanning the sample and acquiring the data is computer controlled. The computer may also be used for enhancing the image with the help of image processing as well as performing quantitative measurements.

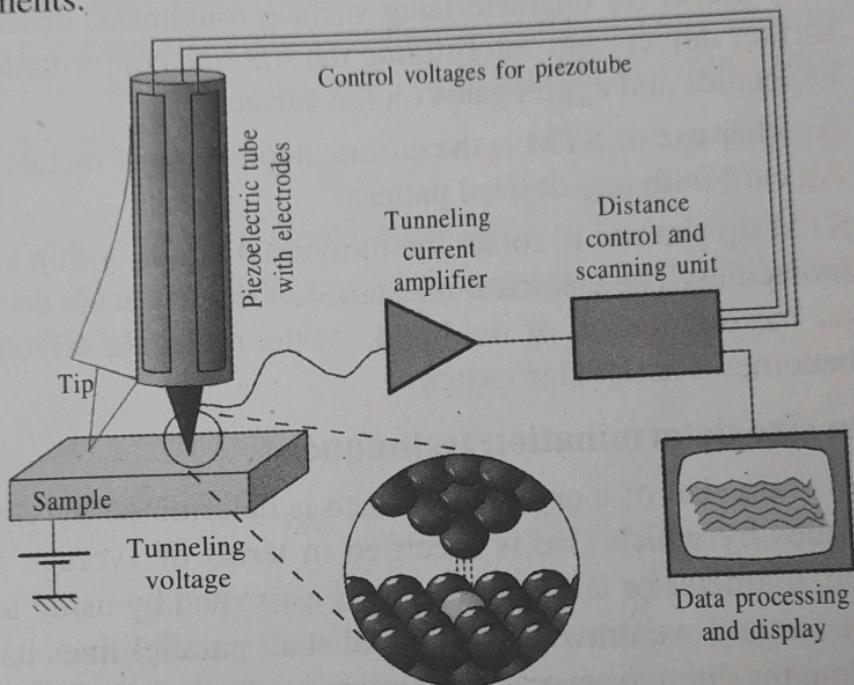


Figure : 8.8: Schematic view of an STM

### Working

Firstly a voltage bias is applied and the scanning tip is brought close to the sample by means of coarse sample to tip control. Fine control of the tip in all three directions when near the sample is typically piezo electric.

In this situation the voltage bias will cause electrons to tunnel between the tip and the sample, creating a current that can be measured. Once tunneling is established, the tips bias and position with respect to the sample can be varied and data is obtained from the resulting changes in current. If the tip is moved across the

sample in the x-y plane, the changes in surface height and density of states changes in current. These changes are mapped in images.

### Uses of STM

- (i) To obtain atomic scale images of metal surfaces.
- (ii) It provides a three dimensional profile of the surface which is very useful for characterising surface roughness, observing surface defects and determining the size and conformation of molecules and aggregates on the surface.
- (iii) Another use of STM is the atomic deposition of metals (Au, Ag etc.) with any desired pattern.
- (iv) STM tip can use to rotate the individual bonds within single molecules. The electrical resistance of the molecule depends on the orientation of the bond, so the molecule effectively becomes a molecular switch.

### Grain size determination technique

The grain size of a crystal specimen is determined by various techniques by which size is specified in terms of average grain volume, diameter or area. Grain size is estimated by using an intercept method we draw several equidistant parallel lines having equal lengths through several photomicrographs that show the grain structure. The grains intersected by each line segment are counted. The line length is then divided by an average of the number of grains intersected, taken over all the line segments. This number is divided by the linear magnification of the photomicrographs gives the average grain diameter.

Usually grain size is expressed as the grain size number by comparing our result to the standard chart of different average grain sizes.

To each grain size a number is assigned ranging from 1 to 10. The American society for testing and materials (ASTM) has prepared several comparison charts, all having different average grain

sizes. To each is assigned a number ranging from 1 to 10, which is termed as grain size number. A specimen must be properly prepared to reveal the structure, which is photographed at a magnification of 100X. The grain size is expressed as the grain size number of that chart that most nearly matches the grains in the micrograph. Grain size is used extensively in the specification of steels.

Let  $n$  represent the grain size number and  $N$  the average number of grains per square inch at a magnification of 100X. Then  $n$  and  $N$  are related by

$$N = 2^{n-1}$$

This is valid for the magnification 100X.

If  $N_M$  is the number of grains per square inch at magnification  $M$ , the above formula becomes

$$N_M \left( \frac{M}{100} \right)^2 = 2^{n-1}.$$

For the magnification 100,

$$N_{100} = \frac{\text{number}}{\text{area}}$$

Thus for unit magnification

$$N_i = \frac{\text{number}}{\text{area}/100^2}$$

∴ For  $M$  magnification

$$N_M = \frac{\text{Number}}{\text{area } M^2} 100^2$$

Remember that 100X is the linear magnification so the areal magnification is  $100^2X$ .

or 
$$N_M = \left( \frac{M}{100} \right)^2 = \frac{\text{Number}}{\text{area}} = 2^{n-1}$$

# UNIVERSITY MODEL QUESTIONS

## Section A

*(Answer questions in two or three sentences)*

### **Short answer type questions**

1. What is diffraction?
2. Write down Bragg's equation and explain the symbols used.
3. What are the uses of X-ray diffraction method?
4. Explain why X-ray diffraction method is suitable for the analysis of crystal structures.
5. Why zeroth order diffraction is not considered in X-ray diffraction.
6. Why cannot ordinary optical grating diffract X-rays?
7. What are structural elements? Name two of them.
8. What is microscopy?
9. What are microstructures of materials?
10. What are the two devices used for microscopy?
11. What is meant by optical microscopy?
12. What is a light optical microscope?
13. What is electron microscopy?
14. The resolving power of the electron microscope is very high. Explain.
15. Which are the two main types of electron microscope?
16. What is a transmission electron microscope?
17. Why the specimen material is made very thin under the investigation of TEM?
18. What is meant by scanning probe microscopy?
19. What is an SPM?
20. Define resolving power of a microscope? How it can be increased?
21. Define grain size number?
22. What is the relation connecting between the average number of grains per unit area and the grain size number?

23. The grain size number of steel is 3. What does it mean?
24. What is the relevance of 100X magnification with regard to grain size number?
25. Write down the relation between the grain size number and the number of grains per unit area involving magnification?

### Section B

(Answer questions in a paragraph of about half a page to one page)

#### Paragraph / Problem type questions

1. Explain the rotating crystal method.
2. Explain the powder crystal method.
3. Derive Bragg's law.
4. Write a note on structural elements.
5. Explain what is meant by microscopy.
6. Explain the metallographic technique.
7. What is meant by etching process?
8. Distinguish between electron microscope and optical microscope.
9. Explain the working principle of electron microscope.
10. Explain the scanning electron microscopy.
11. Why is necessary to make the specimen surface electrically conductive under the investigation of scanning electron microscope?
12. Distinguish between TEM and SPM.
13. What are the advantages of STM over EM?
14. What are the uses of electron microscopes?
15. What is a scanning tunnelling microscope? Which is its principle?
16. What are the uses of STM Explain?
17. Explain how the grain size of a crystal specimen is determined.
18. What is ASTM? What is its function?
19. The spacing between successive (100) planes in NaCl is  $2.82\text{ \AA}$ . X-rays incident on the surface of the crystal is found to give rise to first order Bragg reflection at glancing angle  $8.8^\circ$ . Calculate the wavelength of X-rays. [0.863  $\text{\AA}$ ]